A new experiment for the determination of the ${}^{18}F(p,\alpha)$ reaction rate at nova temperatures

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Abstract. The ${}^{18}F(p,\alpha){}^{15}O$ reaction was recognized as one of the most important for gamma ray astronomy in novae as it governs the early 511 keV emission. However, its rate remains largely uncertain at nova temperatures. A direct measurement of the cross section over the full range of nova energies is impossible because of its vanishing value at low energy and of the short ${}^{18}F$ lifetime. Therefore, in order to better constrain this reaction rate, we have performed an indirect experiment taking advantage of the availability of a high purity and intense radioactive ${}^{18}F$ beam at the Louvain La Neuve RIB facility. We present here the first results of the data analysis and discuss the consequences.

INTRODUCTION

Gamma–ray emission from classical novae is dominated, during the first hours, by positron annihilation resulting from the beta decay of radioactive nuclei. The main contribution comes from the decay of ¹⁸F (half–life of 110 mn) and hence is directly related to ¹⁸F formation during the outburst. (See the astrophysical discussions in references [1, 2, 3] and by Hernanz in these proceedings.) A good knowledge of the nuclear reaction rates of production and destruction of ¹⁸F is required to calculate the amount of ¹⁸F synthesized in novae and the resulting gamma–ray emission. The rate (see ref. [4]) relevant for the main mode of ¹⁸F destruction (i.e., through ¹⁸F(p, α)¹⁵O) has been the object of many recent experiments[5, 6] (see also Bardayan in these proceedings and refs. in [3]). However, this rate remains poorly known at nova temperatures (lower than 3.5×10^8 K) due to the scarcity of spectroscopic information for levels near the proton

threshold in the compound nucleus ¹⁹Ne. This uncertainty is directly related to the unknown proton widths (Γ_p) of the first three levels (E_x , $J^{\pi} = 6.419$ MeV, $3/2^+$; 6.437 MeV, $1/2^-$ and 6.449 MeV, $3/2^+$). The tails of the corresponding resonances (at respectively $E_R = 8$ keV, 26 keV and 38 keV) can dominate the astrophysical factor in the relevant energy range[3]. As a consequence of these nuclear uncertainties, the ¹⁸F production in nova and the early gamma-ray emission is uncertain by a factor of 300[3]. This supports the need of new experimental studies to improve the reliability of the predicted annihilation gamma-ray fluxes from novae.

EXPERIMENT

A direct measurement of the relevant resonance strengths is impossible because they are at least ten orders of magnitude smaller than the weakest directly measured one (at $E_R = 330 \text{ keV}$;[7] and Bardayan, these proceedings) due to Coulomb barrier penetrability. Hence, we used an indirect method aiming at the determination of the one nucleon spectroscopic factors (*S*) in the analog levels of the mirror nucleus (¹⁹F) by a neutron transfer reaction: D(¹⁸F,p)¹⁹F. (Analog, levels expected to have similar nuclear properties have been identified in ¹⁹F and ¹⁹Ne spectra[8].) From the spectroscopic factors it is possible to calculate the proton widths through the relation $\Gamma_p = S \times \Gamma_{\text{s.p.}}$ where $\Gamma_{\text{s.p.}}$ is the single particle width readily obtained from a model. The main reason for the choice of a transfer reaction is the much higher reaction cross-section as compared to the direct proton capture. The spectroscopic factors, *S*, are extracted from the angular distribution of the escaping nucleon via the relation:

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = C^2 S \left(\frac{d\sigma}{d\Omega}\right)_{DWBA} \tag{1}$$

Where the $(d\sigma/d\Omega)_{exp}$ is the experimental angular distribution of the protons from the D(¹⁸F,p)¹⁹F reaction while $(d\sigma/d\Omega)_{DWBA}$ is the theoretical one (Distorded Wave Born Approximation) and C^2 is a known coefficient.

Since ¹⁸F is a short lived (110 mn) radioactive isotope, it cannot be used as a target. It must be first produced, then accelerated and directed to the deuterium target (inverse kinematics). We performed the experiment at the *Centre de Recherche du Cyclotron* in Louvain–La–Neuve (Belgium) where such a beam has been developed. The ¹⁸F is produced through the ¹⁸O(p,n) reaction, chemically extracted to form CH₃¹⁸F molecules, transferred to the cyclotron source[9] and accelerated to 14 MeV. The targets are made of deuteriated polypropylene (CD₂) of $\approx 100 \ \mu g/cm^2$ thickness. For the energy considered here (1.4 MeV in the center of mass), the deuteron and the outgoing proton are both below the Coulomb barrier. The major advantages is a reduction of the contribution of compound-nucleus reactions leading to a better extraction of spectroscopic factors. The experimental setup is depicted in Figure 1. It consists of two silicon multistrip detectors composed of sectors with 16 concentric strips (of 5 mm width) built by the Louvain–La–Neuve and Edinburgh collaboration[10]. They measure the angle (strip number), energy and time of flight (for particle identification) of the particles. One, LAMP, is positioned 9 cm upstream from the target; it consists of 6 sectors forming a conical



FIGURE 1. Experimental setup.

shape to optimize angular coverage. With such a geometry, it covers laboratory angles between 115° and 160° i.e. forward center of mass angles between 12° and 40° providing a good acceptance for protons in the domain of interest for the differential cross section. Indeed, the proton angular distribution as measured in LAMP is the $(d\sigma/d\Omega)_{exp}$ term in eq. 1. The other detector, LEDA, is made up of 8 sectors forming a disk positioned 40 cm downstream from the target and is used for background reduction and normalization. The levels of interests are situated high above the alpha emission threshold (at 4.013 MeV) and their almost exclusive decay mode is through ¹⁹F* \rightarrow ¹⁵N+ α . Hence, to reduce background, we required coincidences between a proton in LAMP and a ¹⁵N (or α discriminated by time of flight) in LEDA. Following Monte Carlo simulations, the exact positions of the two detectors have been chosen to optimize resolution and acceptance. The proton detection efficiency is found to be 24% and is only slightly reduced to 19% when the coincidence condition is applied. Rutherford elastic scattering of ¹⁸F on Carbon from the target, detected in LEDA, provide the (target thickness) × (beam intensity) normalization.

RESULTS

During the 7 days experiment, 15 bunches of ≤ 1 Ci of ¹⁸F were produced providing each a mean beam intensity of 5×10^6 particles per second over a period of ≈ 2 hours. The beam contamination (by ¹⁸O) was found to be smaller than 10^{-3} . Thanks to the kinematics, at this low energy, only light particles (p and α from D(¹⁸F,p)¹⁹F and D(¹⁸F,\alpha)¹⁶O)



FIGURE 2. Reconstructed ¹⁹F spectrum (corresponding to 65% of the total statistics) showing the two $3/2^+$ levels of astrophysical interest around 6.5 MeV of excitation energy.

can reach LAMP while the coincidences with LEDA provide a further selection. The excitation energy of the decaying ¹⁹F levels can be kinematically reconstructed from the energies and angles of the detected protons and the known beam energy. The corresponding spectrum is represented in Figure 2 where vertical lines represent the known position of the ¹⁹F levels. The resolution is not sufficient to separate the various levels but the two $3/2^+$ levels of interest at 6.497 and 6.528 MeV (the analogs of the $3/2^+$ levels in ¹⁹Ne) are well separated from the other groups of levels. There is no peak corresponding to the $1/2^-$ level because it is so broad ($\Gamma_T = 220$ keV) that it cannot be disentangled from the background. The angular distribution, $(d\sigma/d\Omega)_{exp}$, obtained from the data corresponding to the 6.5 MeV peak, i.e. the $3/2^+$ levels, is in good agreement[11] with the theoretical one $(d\sigma/d\Omega)_{DWBA}$ (using nuclear potentials from ref. [12]) providing evidence that the analysis is reliable (e.g. negligible compound nucleus contribution and $\ell = 0$ transferred angular momentum). Since the two $3/2^+$ levels are not resolved, eq. 1 gives the sum of the two spectroscopic factors: $S_1 + S_2 \approx 0.2$. The important consequence of this preliminary value is that the contribution of these resonances to the rate cannot be neglected but that the nominal rate $(S_1 = S_2 \approx 0.1)$ used in gamma–ray flux calculations is not ruled out. However, the extreme case where $S_1 \approx 0.2$, $S_2 = 0$ and $S_1 = 0$, $S_2 \approx 0.2$ have also to be considered to obtain upper and lower rate limits. Figure 3 shows the present reduction on ${}^{18}F(p,\alpha){}^{15}O$ rate uncertainty brought by this experiment. Hopefully, progress in the data analysis (energy calibration and normalization) will further reduce this uncertainty but new experiments are required to obtain a reliable reaction rate for nova gamma-ray flux calculations.



FIGURE 3. Present reduction on rate uncertainties (hatched area) brought by the experiment compared with previous limits[3]. (Ratios are with respect to the Wiescher and Kettner rate[4].) Note that part of the remaining uncertainty is due to the $1/2^{-1}$ resonance.

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